# Multi-symbol Detection for Ultra-wideband PPM Communications in Multipath Environments

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***Abstract*— A multi-symbol detection(MSD) method based on the approximation of ML decoding for detecting the signal modulated by PPM in unknown UWB channels is investigated. The explicit expression of the achievable rates of PPM with MSD is derived, from which we study the relationship between the achievable rates, SNR and channel bandwidth. The numerical results show that multi-symbol detection significantly improves the achievable rates over conventional non-coherent detection. When channel bandwidth tends to infinity, as long as symbol number $N$ keeps up with the resolvable multipath number $L$, the achievable rates will tend to AWGN capacity.**

## I. Introduction

Ultra-wide bandwidth communication is a regime that usually utilizes very narrow pulse to transmit information [1]∼[3]. Due to its ultra-wide bandwidth, very high power efficiency can be achieved and vast data rate can be implemented under extremely low power spectrum density(PSD). Low PSD will benefit to the coexistence with other systems and ultra-short pulse duration will help to dramatically suppress the multipath fading.

In the past few years, several feasible modulation schemes for UWB communications such as PPM, DSSS and OFDM have drawn a number of research attentions from information theory perspective. [4] [5] studied the mutual information transferred by DSSS modulation in the absence of CSI, they concludes that the mutual information will converge to zero when the bandwidth tends to infinity and the multipath number grows with the bandwidth. This is due to the fact that as the power of the signal is limited, a large number of multipath will lead to much less energy in each path so that the performance will be deteriorated asymptotically by the channel uncertainty. [6] considered the influence of duty cycle on the capacity of DSSS and PPM modulation which shows that if the multipath number $L$ increases slowly enough compared with the bandwidth, both $C_{DSSS}$ and $C_{PPM}$ can approach $C_{AWGN}$. [7] studied the behavior of OFDM system in the time-variant multipath channel. The system capacity will begin to decrease when the bandwidth exceeds a value which is called critical bandwidth, provided that the product of the maximum delay and Doppler shift $\tau_0\nu_0$ keeps constant. The critical bandwidth will grow inversely with $\tau_0\nu_0$, since the smaller $\tau_0\nu_0$ the slower channel varies.

In this paper, we study the rules that the achievable rate of PPM varies with the bandwidth from a point view of optimal demodulation with the assumption of unknown UWB channel.

To detect signals modulated by PPM, methods like envelope detection are usually applied which results in the achievable rate being much less than that achieved with known CSI. The investigation of [8] shows that the achievable rates of PPM with conventional non-coherent detection will diminishes with the increasing bandwidth. Conventional non-coherent detection assumes the independent realizations of the channel along with different symbols. In practical communication systems, however, the channel undergone by adjacent symbols will have a certain dependency even when time-variant is taken into account. In a slow fading channel, the multipath delays and gains can be assumed to be invariable during the channel coherence time. Taking advantage of this characteristic, the performance of non-coherent detection will be significantly improved with multiple symbol joint detection. In [9] a multi-symbol differential detection(MSDD) was proposed, which is a detection method based on ML criterion for detecting the signals modulated by MPSK in AWGN channel. As the number of symbols tends to infinity, MSDD will achieve the performance of coherent detection. [10] studied the MSDD in diversity fading channel for MPSK demodulation recently. It also reports that the performance of optimal combining can be implemented by this approach when CSI is not known. To analyze the achievable rate of PPM with optimal decoder for unknown CSI, we start from deriving the ML detection for PPM in unknown UWB multipath channel with the gains being Nakagami-$m$ distribution [11]. For reducing the complexity, we further develop a sub-optimal approximation of the ML detection which is termed as multi-symbol detection(MSD). The upper bound of the detection error probability of MSD is derived by the Chernoff bound and random coding rule, the analytical expression of the achievable rates is therefore achieved. Numerical results can be easily obtained with this formula, even in the more general scenario that the multi-path signals of different time slots are overlapped. In the experiments, the achievable rates along with symbol number $N$ and channel bandwidth are investigated and compared with that achieved by conventional non-coherent detection [8]. The results demonstrate nearly an order of magnitude improvement, and the achievable rate of MSD can gradually approach the wideband capacity with the augmentation of $N$. In this way MSD may bridge the gap between the achievable rates of PPM with known CSI and unknown CSI.

The remainder of this paper is organized as follows. In section II, PPM scheme, UWB multipath channel model and the received signal are described. In section III, multi-symbol detection for PPM based on ML criterion is presented. The achievable rate of MSD is derived in section IV and the numerical results and comparison are presented in section V. The last section is conclusions.

## II. System Description

### A. Pulse Position Modulation

PPM is a modulation method that using the position of the pulse to transmit information. A symbol duration can be divided to $m$ time slots and each of them can be occupied to transmit a pulse. Assume a code set $\{C_0, C_1, \cdots, C_{M-1}\}$ that has a dimension of $M$, in which every codeword is a sequence of length $N$ and represents $N$ symbols. For example, $C_k = (c_{0,k}, c_{1,k}, \cdots, c_{N-1,k})$, in which $c_{n,k} \in \{0, \ldots, m-1\}$ is the slot number that each symbol occupied. The duration of a symbol is defined as $T_s$ and the duration of a time slot is equal to that of a pulse $T_p$. To avoid the interference between symbols, $T_s = mT_p + T_d$ is assumed where $T_d$ is the guard time and is often assigned as the maximal multipath delay. Hence, when codeword $C_w$ is transmitted, the transmitted signal can be expressed as

$$x_w(t) = \sum_{n=0}^{N-1} \sqrt{E_s}\phi(t - nT_s - c_{n,w}T_p), \tag{1}$$

where $\phi(t)$ is the transmitted pulse whose energy is normalized.

### B. UWB Channel Model

There are two salient differences between the UWB channel considered here and the conventional narrow band channel. One is that UWB channel is real because of no carrier existing in the PPM signal by direct transmitting ultra narrow pulse. The other is that UWB channel often has much less fading, since there are not a great number of pulse with random phase to be added together for the very short pulse. Thus, the gains of the multipath in UWB channel are no longer Rayleigh distribution. [11] proposed that when the delay $\tau_l$ is equally spaced the gain $\alpha_l$ submits to Nakagami-$m$ distribution. The impulse response of the channel is denoted as

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l), \tag{2}$$

where $L = \lfloor \frac{T_d}{T_p} \rfloor + 1$ is the multipath number. [12] pointed out that the phase of the signal may be reversed by the reflections, the sign of $\alpha_l$ should be equiprobably positive or negative. Hence, the probability density function of $\alpha_l$ is

$$p(\alpha_l) = \begin{cases} \frac{1}{\Gamma(m_l)} \left(\frac{m_l}{\Omega_l}\right)^{m_l} \alpha_l^{2m_l-1} e^{-m_l\alpha_l^2/\Omega_l}, & \alpha_l \geq 0 \\ \frac{1}{\Gamma(m_l)} \left(\frac{m_l}{\Omega_l}\right)^{m_l} (-\alpha_l)^{2m_l-1} e^{-m_l\alpha_l^2/\Omega_l}, & \alpha_l < 0 \end{cases} \tag{3}$$

where $m_l$ and $\Omega_l$ are the fading figure and mean square of $\alpha_l$, respectively. In addition, we consider the slow fading channel in deriving the detection method and achievable rate, which means that the channel coherence time $T_c$ will always be greater than the codeword duration $NT_s$.

### C. Received Signal

The received signal of PPM passing through multipath channel can be written as,

$$\begin{aligned} r(t) &= x_w(t) * h(t) + n(t) \\ &= \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} \sqrt{E_s}\alpha_l \phi(t - nT_s - c_{n,w}T_p - \tau_l) + n(t), \end{aligned} \tag{4}$$

where $n(t)$ is the white Gaussian noise. After matched filter and analog-to-digital converter, the $j$th sample signal in the $n$th symbol is

$$r_{j,n} = \int_{-\infty}^{\infty} r(t)\phi(t - nT_s - jT_p)dt, \quad j \in \left[0, \frac{T_s}{T_p}\right]. \tag{5}$$

Define $J = \lfloor \frac{T_s}{T_p} \rfloor + 1$, $\mathbf{r}_n = [r_{0,n}, \cdots, r_{J-1,n}]^T$. When $C_w$ is transmitted, define $\mathbf{s}_{n,w} = [0, \cdots, \mathbf{h}^T, \cdots, 0]^T$, where $\mathbf{h} = [\alpha_0, \cdots, \alpha_{L-1}]^T$,$\|\mathbf{h}\|^2 = 1$, the start position of $\mathbf{h}$ is $c_{n,w}$. Then

$$\mathbf{r}_n = \sqrt{E_s}\mathbf{s}_{n,w} + \mathbf{z}_n,$$

where $\mathbf{z}_n$ is a Gaussian noise vector with zero mean and covariance matrix $\mathbf{R}_z = E[\mathbf{z}_n\mathbf{z}_n^T] = \frac{N_0}{2}\mathbf{I}$.

## III. Multi-symbol Detection

Since the concept of multi-symbol detection comes from ML detection with unknown CSI in receiver, we start from deriving the optimal detection method for PPM in typical UWB channel. According to ML criterion, the output of the detector should be the codeword that makes the conditional probability of the received sequence be maximal, *i.e.*,

$$C_w = \arg\max_{C_k} p(\mathbf{r}|C_k), \tag{6}$$

where $\mathbf{r} = [\mathbf{r}_0^T, \cdots, \mathbf{r}_{N-1}^T]^T$.

Since $\mathbf{z}_n$ is a Gaussian noise vector, $\mathbf{r}$ submits to multivariate Gaussian distribution when the transmitted codeword $C_k$ and channel gains $\mathbf{h}$ are known. The conditional probability of $\mathbf{r}$ is then,

$$\begin{aligned} p(\mathbf{r}|C_k, \mathbf{h}) = \pi^{-NJ}|\mathbf{R}_z|^{-N} & \\ \cdot \exp\Bigg\{ -\sum_{n=0}^{N-1} \left(\mathbf{r}_n - \sqrt{E_s}\mathbf{s}_{n,k}\right)^T & \\ \cdot \mathbf{R}_z^{-1} \left(\mathbf{r}_n - \sqrt{E_s}\mathbf{s}_{n,k}\right) \Bigg\}. & \end{aligned} \tag{7}$$

Considering the received signal model of PPM, it can be simplified as

$$p(\mathbf{r}|C_k, \mathbf{h}) = A_1 \cdot \prod_{l=0}^{L-1} \exp\left\{\frac{4}{N_0}\sqrt{E_s}y_{l,k}\alpha_l\right\}, \tag{8}$$

where

$$A_1 = \pi^{-NJ} |\mathbf{R}_z|^{-N} \exp\{-\frac{2}{N_0} A_0\},$$

$$A_0 = \sum_{n=0}^{N-1} \sum_{j=0}^{J-1} r_{j,n}^2 + NE_s, \quad y_{l,k} = \sum_{n=0}^{N-1} r_{c_{n,k}+l,n}.$$

Since the path gains in UWB channel are independent, we have $p(\mathbf{h}) = \prod_{l=0}^{L-1} p(\alpha_l)$. After some manipulations the conditional probability in unknown UWB channel can be obtained as

$$\begin{aligned} p(\mathbf{r}|C_k) &= \int_{-\infty}^{\infty} p(\mathbf{r}|C_k, \mathbf{h}) p(\mathbf{h}) d\mathbf{h} \\ &= A_1 \cdot \prod_{l=0}^{L-1} \left\{ \Phi\left( m_l, \frac{1}{2}; \frac{4E_s \Omega_l y_{l,k}^2}{{N_0}^2 m_l} \right) \right\}, \end{aligned} \quad (9)$$

where $\Phi(\alpha, \gamma; z)$ is a confluent hypergeometric function which is defined as

$$\begin{aligned} \Phi(\alpha, \gamma; z) &= \frac{\Gamma(\gamma)}{\Gamma(\alpha)} \sum_{n=0}^{\infty} \frac{\Gamma(n+\alpha)}{\Gamma(n+\gamma)} \frac{z^n}{n!} \\ &= 1 + \frac{\alpha}{\gamma} \frac{z}{1!} + \frac{\alpha(\alpha+1)}{\gamma(\gamma+1)} \frac{z^2}{2!} \\ &\quad + \frac{\alpha(\alpha+1)(\alpha+2)}{\gamma(\gamma+1)(\gamma+2)} \frac{z^3}{3!} + \cdots . \end{aligned} \quad (10)$$

When $\alpha = \gamma$, $\Phi(\alpha, \gamma; z) = e^z$, that means when $m_l = \frac{1}{2}$

$$p(\mathbf{r}|C_k) = A_1 \cdot \exp\left\{ \sum_{l=0}^{L-1} \frac{4E_s \Omega_l y_{l,k}^2}{{N_0}^2 m_l} \right\}. \quad (11)$$

From (9) the decision statistics of optimal demodulation for PPM in unknown UWB channel can be obtained, but its computation is rather involved and a sub-optimal algorithm is expected. From (11) and the relation between $\Phi(\alpha, \gamma; z)$ and $e^z$ we can get an approximate demodulation as

$$\begin{aligned} C_w &= \arg\max_{C_k} p(\mathbf{r}|C_k) \\ &\simeq \arg\max_{C_k} \left\{ \sum_{l=0}^{L-1} \frac{4E_s \Omega_l y_{l,k}^2}{{N_0}^2 m_l} \right\}. \end{aligned} \quad (12)$$

In the practical systems, the statistic information of the channel such as $m_l$ and $\Omega_l$ may not be known *a priori*. In this case, by assuming $m_l$ and $\Omega_l$ are invariant with $l$ we have

$$C_w \simeq \arg\max_{C_k} \left\{ \sum_{l=0}^{L-1} y_{l,k}^2 \right\}. \quad (13)$$

which is the sub-optimal multi-symbol detection method that we strive for detecting the PPM signals in UWB communications.

## IV. Achievable Rates of MSD

In this section, we investigate the achievable rate of the PPM with MSD given by (13). Set the decision variable as

$$Y_k = \frac{1}{N^2} \sum_{l=0}^{L-1} Y_{l,k} = \frac{1}{N^2} \sum_{l=0}^{L-1} y_{l,k}^2,$$

and the threshold rule is utilized to detect the PPM signal. $C_w$ is regarded as the transmitted codeword when only one $k = w$ exists for $Y_k$ exceeding a threshold $\delta$. All other cases will be regarded as decision errors. In order to obtain the achievable rate, we first derive the error probability as follows.

Set the threshold $\delta = (1 - \epsilon) E_s$. When $N$ approaches infinity, for any $\epsilon > 0$ the probability that $Y_w$ exceeds the threshold will close to 1 arbitrarily. For all $k \neq w$, using Chernoff bound [13] the probability that $Y_k \geq \delta$ can be calculated as

$$\begin{aligned} Pr(Y_k \geq \delta) &= Pr(N^2 Y_k \geq N^2 \delta) \\ &\leq \min_{s>0} e^{-sN^2\delta} \prod_{l=0}^{L-1} E[\exp(s y_{l,k}^2)]. \end{aligned} \quad (14)$$

Since $Y_{l,k} = y_{l,k}^2$, $E[\exp(s y_{l,k}^2)]$ can be obtained by calculating the moment-generating function of random variable $Y_{l,k}$. Define $\tilde{r}_{c_{n,k}+l,n}$ as the signal component of the sampled signal $r_{c_{n,k}+l,n}$ without noise, $\tilde{r}_{c_{n,k}+l,n}$ might equal to $\alpha_{l'}, l' \neq l$ or zero. However, this does not mean that $\tilde{r}_{c_{n,k}+l,n}$ is a random variable. In fact, $\tilde{r}_{c_{n,k}+l,n}$ is a determined value when $C_k$ and the channel are fixed. Thus being the signal part of $y_{l,k}$, $\tilde{y}_{l,k} = \sum_{n=0}^{N-1} \tilde{r}_{c_{n,k}+l,n}$ is also not random. Therefore, $Y_{l,k}$ is non-central $\chi^2$ distribution, its moment-generating function is,

$$E[e^{sY_{l,k}}] = (1 - NN_0 s)^{-\frac{1}{2}} \exp\left\{ \frac{s}{1 - NN_0 s} \tilde{y}_{l,k}^2 \right\}. \quad (15)$$

Consequently,

$$\begin{aligned} &\prod_{l=0}^{L-1} \left\{ E[\exp(s y_{l,k}^2)] \right\} \\ &\quad = (1 - NN_0 s)^{-\frac{L}{2}} \exp\left\{ \frac{s}{1 - NN_0 s} \sum_{l=0}^{L-1} \tilde{y}_{l,k}^2 \right\}. \end{aligned} \quad (16)$$

Since

$$\begin{aligned} \sum_{l=0}^{L-1} \tilde{y}_{l,k}^2 &= \sum_{l=0}^{L-1} \left( \sum_{n=0}^{N-1} \tilde{r}_{c_{n,k}+l,n} \right)^2 \\ &= \sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \tilde{r}_{c_{n,k}+l,n}^2 + 2 \sum_{l=0}^{L-1} \sum_{i,j=0}^{N-1} \tilde{r}_{c_{i,k}+l,i} \tilde{r}_{c_{j,k}+l,j} \\ &\qquad (i \neq j) \end{aligned}$$

and

$$\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \tilde{r}_{c_{n,k}+l,n}^2 = \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} \tilde{r}_{c_{n,k}+l,n}^2 \leq NE_s$$

$$\sum_{l=0}^{L-1} \sum_{i,j=0}^{N-1} \tilde{r}_{c_{i,k}+l,i} \tilde{r}_{c_{j,k}+l,j} \simeq 0 \quad (i \neq j, \ N \to \infty),$$

we have

$$\prod_{l=0}^{L-1}\left\{E[\exp(sy_{l,k}^2)]\right\} \leq (1-NN_0s)^{-\frac{L}{2}}\exp\left\{\frac{s}{1-NN_0s}NE_s\right\} \quad (17)$$

and

$$Pr(Y_k \geq \delta) \leq \min_{s>0} e^{-sN^2\delta}(1-NN_0s)^{-\frac{L}{2}}\exp\left\{\frac{s}{1-NN_0s}NE_s\right\}. \quad (18)$$

Because each of the $M$ codewords has chance to exceed the threshold, according to the union bound, we have the error detection probability

$$P_e \leq M\min_{s>0} e^{-N\left(sN\delta+\frac{L}{2N}\ln(1-NN_0s)-\frac{s}{1-NN_0s}E_s\right)}. \quad (19)$$

It seems that the common factor of the exponential term is $N^2$ in this formula, but for the AWGN channel we can prove that

$$P_e \leq Me^{-N\left(\frac{E_s}{N_0}-\frac{L}{2N}-\frac{L}{2N}\ln\left(\frac{E_s}{N_0}\frac{2N}{L}\right)\right)}, \quad (20)$$

the error probability decreases exponentially with $N$. Since the system in multipath channel can not outperform that in AWGN channel, the common factor in (19) should be $N$.

It is shown from (19) that as long as the data rate

$$R = \frac{1}{NT_s}\log M \leq \max_{s>0}\frac{1}{T_s}\left(sN\delta+\frac{L}{2N}\ln(1-NN_0s)-\frac{s}{1-NN_0s}E_s\right), \quad (21)$$

the error probability will decay to 0 as $N$ tends to infinity.

If $\delta = E_s$then from (21) we have

$$R \leq \max_{s>0}\left(sNP_s+\frac{L}{2NT_s}\ln(1-NN_0s)-\frac{s}{1-NN_0s}P_s\right),$$

where $P_s = E_s/T_s$ is the average received power. Replace $1-NN_0s$ with $p$, and define the ratio of the average received power to the power spectrum density of the noise as $\gamma = P_s/N_0$, then optimize $R$ with $p$ we can get

$$R \leq (1-p)\gamma + \frac{L}{2NT_s}\ln p - \frac{1-p}{p}\frac{\gamma}{N}, \quad (22)$$

and

$$p = \frac{\frac{L}{2T_s}+\sqrt{\left(\frac{L}{2T_s}\right)^2+4N\gamma^2}}{2N\gamma}. \quad (23)$$

In fact, the number of time slot in each symbol is finite such that the data rate will also be constrained by $m$, that is to say

$$R' \leq \frac{1}{T_s}\ln(m) = \frac{1}{T_s}\ln\left(\frac{T_s-T_d}{T_p}\right). \quad (24)$$

Hence, the data rate that PPM with MSD be able to achieve is

$$\bar{R} = \min(R,\ R'). \quad (25)$$

## V. NUMERICAL RESULTS

When all the other system parameters are given, the variable parameter in (22) and (24) is only $T_s$. By searching optimal $T_s$ the maximum of the system achievable rate $\bar{R}_{\max}$ can be obtained. In the subsequent experiments, the results of [8] is also presented for comparison. It is a non-coherent single symbol detection(SSD) method and in its numerical results the time slot is supposed as $T_d + T_p$ to avoid the inter-pulse interference. In the derivations in last section, natural logarithm is used thus the unit of data rate is nats/s, the relation between which and bits/s is $R_n = R_b/\log_2 e$.

Fig. 1 shows the achievable rates versus SNR for bandwidth $B = 1GHz$, pulse duration $T_p = 1/B$ and maximal multipath delay $T_d = 100ns$, where SNR is defined as $P_s/BN_0$. In the figure, the multipath channel capacity with infinite bandwidth, the achievable rate of MSD when $N = L$ and $N = L/10$, and the achievable rate of SSD are illustrated. It is shown that the data rate increases linearly in relatively low SNR, and it is larger for $N = L$ than $N = L/10$ which demonstrates that the achievable rate will close to the capacity as $N$ gets large. When SNR is high enough, data rate using more symbols for detection will not improve any more because (24) tells us that the data rate is constrained by $R'$ as well and $R'$ does not depend on SNR and $N$. Moreover, it can be observed that the achievable rate of MSD is improved upon SSD for nearly an order of magnitude which exhibits the significant advantage of multi-symbol detection.

Fig. 2 shows the optimal symbol duration $T_s$ varies with SNR. It is observed that $T_s$ varies inversely with the average SNR. This is due to the fact that a certain amount of $E_s/N_0$ is required to achieve a low symbol error probability. No matter how low the average SNR is, an amount of peak SNR is necessary for correct detection. When average SNR is small, only extending $T_s$ can ensure the required peak SNR. Consequently, the signal will become more and more peaky as average SNR vanishes.

Fig. 3 studies the effect of bandwidth scaling. In the experiment, $P_s/N_0$ is assumed as 80dB. Note that the average SNR is not fixed because of the variable bandwidth $B$. For a typical UWB environment, the average SNR of the received signal is -10dB after the signal has propagated 10 meters when the bandwidth of transmitted signal is 1GHz, the central frequency is 3.6GHz, the PSD is -41.3dBm/MHz, the path loss exponent is 3, and the noise figure of the receiver is 9dB. As shown from the figure, the achievable rates will diminish to zero along with the continuous bandwidth extending if $N$ keeps constant. However, if $N$ grows with $L$ as bandwidth increases($N = 10$ when $L < 10$), in spite of the CSI is unknown and MSD is a sub-optimal detection, the achievable rate of this system will still approach the AWGN capacity when the bandwidth of both channels tends to infinity. In the case of $N = 100$, the critical bandwidth is 6.3GHz. In a smaller bandwidth than 6.3GHz, $R'_{\max} < R$ and $R'_{\max}$ increases along with bandwidth. When the critical bandwidth is exceeded, $R$ will begin to degrade although $R'$ still increases as $T_p$ gets narrower, this will induce

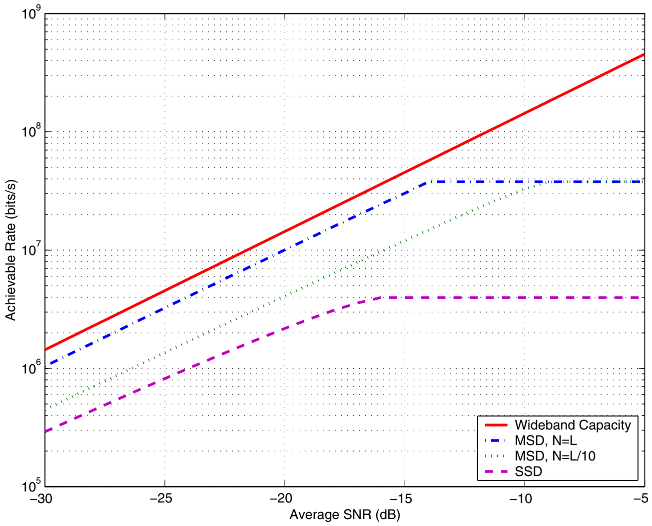


Fig. 1. Achievable rates versus SNR for bandwidth $B = 1GHz$

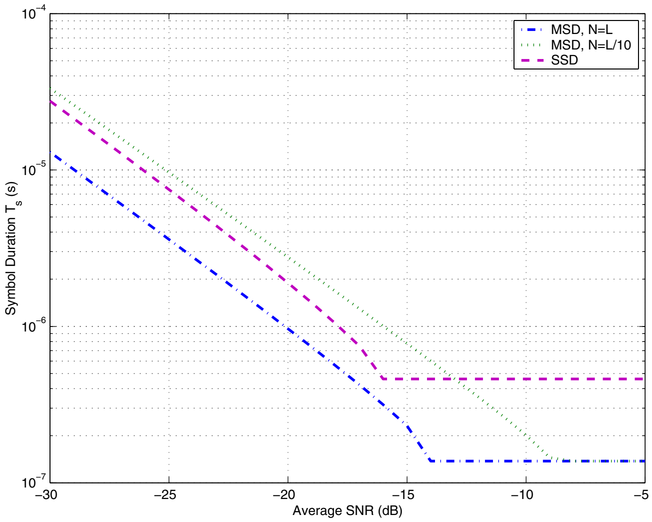


Fig. 2. Symbol duration $T_s$ versus SNR for bandwidth $B = 1GHz$

the gradual decreasing of the final data rate $\max\min(R, R')$. SSD has a similar behavior, but because it dose not utilize the channel coherence and is bounded by the relatively large slot spacing, its achievable rate is far less than that of MSD.

## VI. CONCLUSION

In this paper, a multi-symbol detection approach is presented for ultra-wideband PPM communications, and the achievable rate of PPM applying MSD in multipath environments is derived. Taking advantage of the channel coherence, MSD will significantly improve the achievable rate of PPM in the absence of CSI. Through the numerical analysis, it is shown that the achievable rate increases linearly with the SNR until the restriction of slot number deters it. At the same time, the duration of the symbol varies inversely with the SNR and this causes a more peaky signal in low SNR environments. It is also observed that the achievable rate will achieve the AWGN

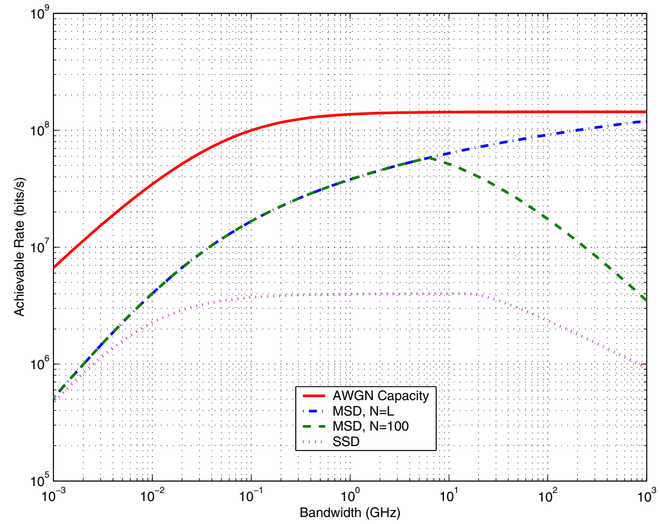


Fig. 3. Achievable rates versus bandwidth for $P_s/N_0 = 80dB$

capacity rather than zero when channel bandwidth tends to infinity if symbol number $N$ grows linearly with the number of resolvable multipath $L$. In the case that $N$ keeps as a constant, however, the achievable rate will gradually diminish when the bandwidth exceeds a critical value since the receiver is not capable to cope with the uncertainty of so many paths.

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